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STORMWATER MANAGEMENT CRITERIA FOR ON-SITE POLLUTION CONTROL – A COMPARATIVE ASSESSMENT OF INTERNATIONAL PRACTICES

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ABSTRACT

Over the last decade, a growing interest has been shown towards innovative stormwater management practices, breaking away from conventional "end of pipe" approaches (based on conveying water offsite to centralized detention facilities). Innovative strategies, referred to as Sustainable Urban Drainage Systems (SUDS), Low Impact Development (LID) or Green-Infrastructures, advocating for management of runoff as close to its origin as possible, have therefore gained a lot of popularity among practitioners and public authorities. However, while the need for pollution control is generally well accepted, there is no wide agreement about management criteria to be given to developers. This article hence aims to compare these criteria through literature analysis of different state or local stormwater management manuals or guidelines, investigating both their suitability for pollution control and their influence on Best Management Practices selection and design. Four categories of criteria were identified: flow rate limitations, "water quality volumes" (to be treated), volume reduction (through infiltration or evapotranspiration), and non-hydrologic criteria (such as loads reduction targets or maximum effluent concentrations).This study suggests that hydrologic criteria based on volume reduction (rather than treatment) might generally be preferable for on-site control of diffuse stormwater pollution. Nonetheless, determination of an appropriate management approach for a specific site is generally not straightforward and presents a variety of challenges for site designers seeking to satisfy local requirements in addressing stormwater quantity and quality issues. The adoption of efficient LID solution may therefore strongly depend on the guidance given to practitioners to account for these management criteria.

KEYWORDS: Guidelines, Pollution control, Review of practices, Runoff management, SUDS

1. INTRODUCTION

While urban runoff used to be merely directed to surface water bodies through combined and separated sewer networks, it is today recognized as a major source of surface water impairment. Since the early eighties, several studies indeed evidenced that urban runoff and combined sewer overflows (CSO) were responsible for surface water quality and biodiversity deterioration (US-EPA 1983; Marsalek 1990; Saget 1994; Herricks 1995). Stormwater management therefore substantially evolved over the last decades. Efforts for mitigation of urban runoff and associated pollutants initially led to the adoption of "end of pipe" strategies, based on the treatment of stormwater collected by sewer networks, prior to its release to the environment (Roy et al. 2008). These conventional approaches however proved to be insufficient due to the limited capacity of drainage systems (often overwhelmed in older cities) and because the adoption of end of pipe treatment facilities would require handling huge runoff volumes (Mitchell 2006). Innovative approaches, referred to as Sustainable Urban Drainage Systems (SUDS),Green-Infrastructures or Low Impact Development (LID), advocating for management of runoff as close to its source as possible in small decentralized best management practices (e.g. rain gardens, bioswales or micro-detention facilities) to preserve natural hydrologic balance and minimize pollutant discharge, have hence gained a lot of popularity among practitioners and public authorities (Ahiablame et al. 2012; Fletcher et al. 2014).

While initially focused on flood mitigation, a broader range of benefits is today expected from stormwater management and LID (Fletcher et al. 2014). Indeed, distributed stormwater control not only reduces peak-flow and volumes so they match drainage systems capacities (Andoh and Declerck 1997), but also provides a cost effective solution (Taylor and Fletcher 2007; Qiu 2013) for water quality improvement through management of nonpoint runoff pollution associated with frequent rain events and moderate contamination levels. Small integrated best management practices (BMPs), such as bio-filtration, are usually promoted because they have been not only shown to efficiently retain runoff (temporarily or not), but also to remove noticeable amounts of stormwater pollutants (Hatt et al. 2009; Gallo et al. 2012). In some cases, stormwater facilities that were not specifically designed for pollution control, but allow for temporary retention of runoff volume and infiltration, were shown to have a significant impact on pollutant loads (Bressy et al. 2014). BMPs' efficiency for pollution control however largely lies in their hydrologic performance. Recent studies indeed indicate that pollutant load reduction mostly tallies with runoff volume reduction, although specific treatment processes (e.g. settling, adsorption…) may also retain contaminants (Davis et al. 2009; Trowsdale and Simcock 2011).

While public authorities emphasize the need to minimize the impacts of stormwater discharge, management criteria given for on-site runoff control significantly differ from one country to another, and the relevance of these criteria is seldom questioned. This article, based on an extensive literature analysis of international practices therefore aims to compare these criteria. After a brief discussion on the importance of institutional and regulatory framework, four categories of stormwater management criteria identified from grey literature (national or regional guidelines, engineering standards, rules or local ordinances) will be presented.

The relevance of these criteria for on site pollution control will be examined, considering (1) the rationale for their definition, (2) how well they reflect the pollution control objective, and (3) discussing whether compliance to these criteria is always likely to provide the expected outcomes. Finally, this study will investigate to what extent management criteria may influence BMP selection and design. More specifically, concerns will be raised about the possible impediments to LID and innovative practices adoption.

2. INSTITUTIONAL FRAMEWORK

Stormwater management governance is usually described as an increasingly cross-organizational and inter-disciplinary process generally involving multiple entities, that does not solely result from legal or normative framework (Brown 2005; Roy et al. 2008; Porse 2013). It has thus to be acknowledged that the influence of "management and design criteria" is only one (mostly technical) aspect of a much wider issue.

At a local scale, stormwater management implementation often results from various rules or engineering standards delivered by public authorities at different institutional levels. "Criteria", as referred to in this article, thus simply consists of numerical targets or management principles given to practitioners for on-site stormwater control, which may not systematically be regulatory and can be found as prescriptions or recommendations. In the US, States have often been delegated the authority to regulate stormwater management through NPDES (National Pollutant Discharge Elimination System) permits issuance. Management criteria may hence either result from States' rules and guidelines or local codes or ordinance set by counties or municipalities (NRC 2009). Likewise, French stormwater management policies depend on various national or regional guidance documents or planning tools, master plans covering smaller territories, and eventually local rules adopted by municipalities (GRAIE 2009). Although stormwater regulation is generally complex and criteria may originate from various entities, two main institutional levels were identified here, namely local authorities and relatively centralized regional or national bodies or agencies.

Prevention of surface water pollution typically pertains to somewhat general objectives identified in most national or regional guidance documents. In most countries, national or regional agencies therefore produce management or design standards afterwards adopted by local communities (e.g. city councils) to regulate stormwater discharge to sewer systems. In the US and Canada local codes (that primarily regulate stormwater discharge) often directly refer to guidelines originating from regional agencies and must comply with federal (US) or provincial (Canada) requirements (BC-MWLAP 2002; CH2MILL 2002; PDEP 2006; PWD 2011). Similarly, in Germany, Switzerland, Sweden or United Kingdom, management criteria may also be found in guidance documents produced at national level by collaborative groups including both water industry and national agencies (Chouli 2006; CIRIA 2007; DWA 2007). Direct discharges to the environment may even require, like in France or in the US, approval of federal or state agencies which is also indicative of their involvement in stormwater management policies implementation (US-EPA 2004; NRC 2009; DDT-03 2011). Water quality management criteria or guidelines therefore often originate from centralized regional or national agencies. It should however be acknowledged that describing stormwater regulation for water quality as a strictly "top-down" process (e.g. from government and regional entities to local communities) may not always be accurate. Some pioneer communities may actually develop their own guidance and management or design criteria, going beyond national standards, like in Maryland where aquatic habitat restoration in the Anacostia river became a key driver for the adoption of innovative and more stringent local stormwater regulations (ARWRP 2010).

On the other hand, although management criteria intended to prevent flooding (e.g. quantity control criteria) or downstream erosion may be encountered in most national or regional guidelines, discharges to sewer systems are often regulated on the basis of criteria emanating from local communities (or sewer networks operators). In the perspective of pollution control, these are therefore mostly subsidiary criteria usually assumed to ensure water quality improvement through combined sewers overflow (CSO) prevention. Philadelphia Stormwater Management Guidance Manual' (PWD 2011) is for example very similar to "Pennsylvania Stormwater Best Management Practices Manual" (PDEP 2006) but additionally requires 17 l/s/ha flow rate control for discharge to city's combined sewers (PWD 2011). Similarly, "Metro Vancouver Source Control Design Guidelines" (GV-SDD 2012) are based on British Columbia's Guidebook (BC-MWLAP 2002), but additionally requires discharge rate to city's drainage network not to exceed 0.25 l/s/ha. There are however exceptions to this rule; in the UK, national guidelines indicate that discharges to both the environment and sewer systems should not exceed 2 l/s/ha (DEFRA 2011).

From French experience, such local "drainage systems-based" criteria may outshine regional or national water quality guidelines, either because assumed to be suitable for pollution control, or because local codes that apply to developers are not totally consistent with national standards given to drainage network operators. Indeed, although recent national or regional guidelines stress the importance of on-site pollution control (CERTU 2003; AESN 2013), flow-rate limitations often remain, in France, the only discharge criteria given to developers by local communities (Petrucci et al. 2013) and treatment devices are usually only required for highly polluted urban areas (e.g. car-parks or fuel transfer stations). Similar situations could be reported elsewhere in Europe or Northern America. In the US, centralized conveyance to detention facilities (which are assumed to provide some pollutant removal) remained the preferred approach in many US communities (Roy et al. 2008) which focus on flow-rate control rather than water quality (Rittenhouse et al. 2006). Likewise, in Canada, Australia, Spain or Sweden, several Stormwater Master Plans or municipal guidelines were found to be mostly focused on quantity rather than quality issues (Momparler and Andrés-Doménech 2007; ISLE 2009; RCC 2011; AE 2012; Matschoss-Falck 2013). Although these documents generally mention regional water quality objectives and encourage on-site runoff and pollutant control, maximum allowable flow-rate or detention requirements (e.g. quantity control) often remains the only criteria for stormwater facilities sizing.

Fragmentation of responsibilities, as identified by Roy et al (2008), and more generally institutional framework can probably explain the lack of coordination or coherence between regional and local efforts for pollution control. Water quality governance has indeed traditionally consisted in a vertical approach to decision-making with local communities being "top-down recipient of State policies", hindering their involvement in the implementation of non-traditional stormwater controls (Brown 2005), and may thus contribute to the persistence of inappropriate management criteria. This resistance to change might also originate from perceived risk associated with adoption of holistic management strategies (Olorunkiya et al. 2012). In France, sewer systems operators rarely give developers specific criteria to prevent pollutants from entering drainage systems because they probably remain more receptive to quantity control issues like urban flooding, rather than surface water pollution (Martin et al. 2007; Aires and Cavailles 2009; Petrucci et al. 2013) even if they are liable for environmental damage. More generally, the lack of institutional capacity and technical expertise are significant impediment to the adoption of innovative approaches at the local scale (Roy et al. 2008; Porse 2013). One could therefore argue that these local criteria may sometimes be erroneously perceived as suitable for pollution control by practitioners, by requiring the use of stormwater BMP (this point is discussed in section 2.1).

3. IDENTIFICATION OF DIFFERENT CRITERIA FOR ON-SITE POLLUTION CONTROL

3. 1. Flow-rate limitations

Peak-flow control is perhaps the most common approach to conventional stormwater management, and generally aims at preventing urban floods or combined sewer overflows during infrequent storms. In Europe and North America, allowable flow-rates are usually justified by (1) drainage network capacity, (2) preservation of downstream “pre-development runoff rate” or (3) maintenance of peak-flow rates in the receiving stream below pre-construction levels to prevent flood and stream channel erosion (Vuathier et al. 2004; Balascio and Lucas 2009; Brown et al. 2010). While generally not accepted as a water quality criterion, it often remains the only numerical target given to developers for on-site stormwater management. The following interpretations may then be put forward to explain this omission of water quality criteria: there seems to be a common belief that (1) pollution control is generally unnecessary unless runoff originates from highly contaminated surfaces (e.g. trafficked roads, metal roofs, gas station…) and (2) that peak-flow control can be a suitable solution for water quality management.

Several local ordinances (France), guidelines (Canada) or planning documents (Denmark) were found to require specific treatment solutions for car parks, trafficked roads or storage areas in addition to flow-rate limitation (NM 2003; CAA 2010; KWL 2012), suggesting that peak-flow control (which generally does not aim at reducing pollutant discharge) would be “suitable” for other urban surfaces. Bressy et al (2011) however demonstrated that micro-pollutant concentrations in runoff could remain significant at an individual lot scale because of pollutant wash-off from building materials or atmospheric deposition. Despite low to moderate contamination levels, such surfaces thus contribute to non point source pollution of surface waters. Furthermore, even if such runoff was “clean”, it should be outlined that simple peak flow control prior to discharge into sewer systems would probably not make much sense for on-site pollution control given the high cross contamination potential during transport in sewer networks (Bressy et al. 2012).

Claiming that peak-flow control does not provide any pollutant reduction would however be inaccurate as delaying runoff requires temporary storage and usually allows for some infiltration or evapotranspiration. Detention may additionally promote specific processes such as particle settling or adsorption of dissolved contaminants. As a consequence, many local ordinances or guidance documents today encourage the implementation of green infrastructures to provide volume or pollution control when a flow-rate criterion is adopted (LSL 2009; Lehoucq et al. 2013; HCC 2014). Similarly, the criterion itself may be envisaged as an instrument to promote more sustainable stormwater management approaches: as outlined by Petrucci (2012) various benefits are thus expected from the most stringent flow-rate limitations (e.g. 1 l/s/ha). Examples from France and Sweden indicate that flow-rate limitations can be intended to reduce runoff volumes entering sewer networks, as an alternative to total infiltration or evaporation (LSL 2009; Lehoucq et al. 2013). Similarly, flow-rate limitation might be considered as relevant for pollution control (MISEN-PL 2008; LSL 2009; DDT-36 2013). Results from Bressy et al (2014) however evidence that, although on-site solutions designed for peak-flow mitigation could achieve significant reduction of both runoff volumes and pollutant loads, their efficiency yet remained variable. Besides, the finding that flow-rate control could actually extend the duration of erosive flows cast doubt on their viability as pollution control strategy (Emerson et al. 2005; Tillinghast et al. 2011; Petrucci et al. 2013). Development and adoption of other management criteria, directly targeting pollution control or volume reduction, would therefore probably be advisable wherever stormwater management remains only based on peak flow reduction.

3. 2. Volumes based approaches

3. 2.1. "Water quality volume" criteria

Definition of a "water quality volume" is probably the most common approach for pollution control. This criterion is widely adopted in Northern America (US and Canada), but also in New Zealand, England (see table 1) or South Africa (Armitage et al. 2012). Contrary to peak-flow control strategies, such a criterion directly aims at reducing surface water impairment through detention and treatment of a given volume. Although water quality volume definition may vary from a country to another, it generally encompasses the following objectives (as summarized in British guidelines); "Capture and treat the runoff from frequent small events and […] a proportion of the initial runoff […] from larger and rarer events" (CIRIA 2007). As detailed in table 1, this criterion is often supposed to enable capture and treatment of 80 to 90% of annual runoff volumes (MDE 2009; ARC 2010a; MDDEP 2012) and is usually expressed as a rainfall depth, either associated with a design storm (for which runoff shall be treated), or simply representing a storage volume (corresponding runoff depth is then computed from rational or "curve number" methods). Few details are however given about the rationale underlying the determination of the amount of water to be captured and volume targets value may thus differ significantly from a community to another (cf. table 1).

Country/Community	Volume targets	Details
US		
Georgia (AMEC and CWP 2001) (regulatory)	31 mm	Storage volume = corresponding runoff depth
Maryland (MDE 2009) (regulatory)	23 to 25 mm	Storage volume = corresponding runoff depth
New-Jersey (NJDEP 2009) (regulatory)	32 mm	Design storm approach
Canada		
Québec (MDDEP 2012) (non-regulatory)	25 mm	Design storm approach
Alberta (AEP 1999) (non-regulatory)	25 mm	Storage volume = corresponding runoff depth
England		
National guidelines (CIRIA 2007) (non-regulatory)	10 to 15 mm	Storage volume (stormwater ponds only)

New Zealand		
National guidelines (NZWERF 2004) (non-regulatory)	15 to 43 mm	Storage volume or Design storm approach
Auckland Region (ARC 2010b) (non-regulatory)	25 mm	Storage volume or Design storm approach
Christchurch City (CCC 2003) (non-regulatory)	25 mm	Storage volume = corresponding runoff depth
Netherlands		
Bloemendaal (GB 2007) (regulatory)	7 mm	Storage volume (expressed as runoff depth)
Aa and Maas (WAM 2011) (regulatory)	2 to 9 mm	Storage volume (expressed as runoff depth)

Table 1 Illustration of "water quality volume" criteria for various communities - Volume targets are expressed as rainfall depth unless specified.

The water quality volume is generally established from the analysis of long-term rainfall records (although design storm approaches may as well be adopted). Many authorities such as Auckland Regional Council or Iowa Department of Natural Ressources (IDNR 2003; ARC 2010a; MDDEP 2012) thus indicate that water quality volume can be computed by identifying a rainfall depth that include up to 80 or 90% of monitored events. In this case, captured volume is however not necessarily equal to 80 to 90% of annual runoff volumes (as depending on rainfall distribution). This statistical analysis proves to lead to very different values depending on rainfall event definition. As shown in Figure 1, using a 15 year long rainfall record (5-min time-step) from Paris urban area with different Minimum Inter-event Times (MIT) between non-zero precipitation records resulted in water quality volumes ranging from 8mm for a 3h MIT to 21mm for a 24h MIT (cf. figure 1).

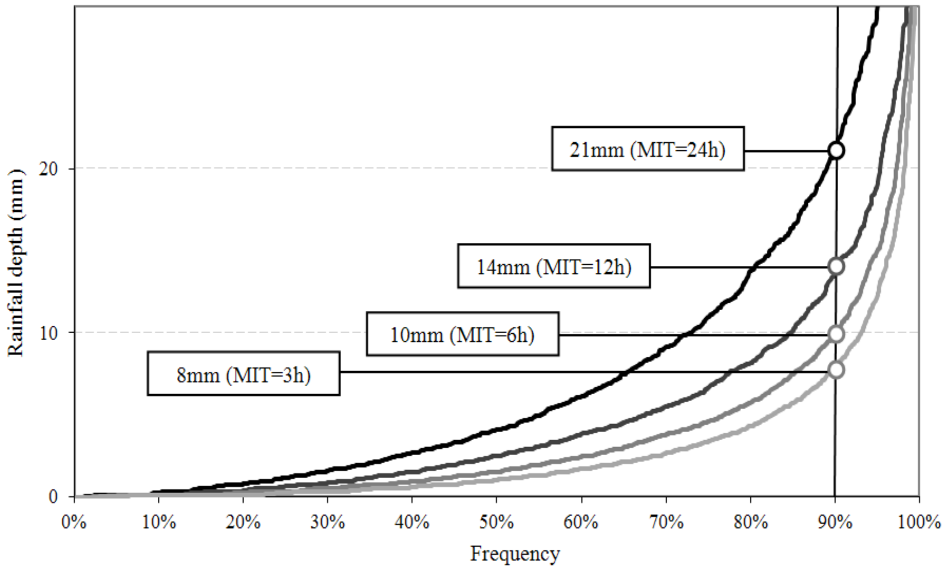

Figure 1 Calculated volume targets depending on rain event definition (MIT = Minimum Intra-event Time) for a 15 year rainfall record from Paris urban area using Auckland Regional Council procedure (ARC 2010a)

More generally, guidance documents analysis indicates that water quality volume is often understood as a storage volume (cf. table 1). The runoff volume intercepted during a given rain events may therefore strongly depend on antecedent weather conditions (Hatt et al. 2009), stormwater facility's design and drawdown requirements. Determining the amount of water captured in a stormwater facility over a year would thus probably require continuous modeling.

Another issue may be that while infiltration, evapotranspiration or re-use are supposedly the preferred approaches to manage the water quality volume (AMEC and CWP 2001; MPCA 2005), treatment and release (e.g. without significant volume reduction) may also be accepted. In the US, although several states explicitly require a fraction of the water quality volume to be infiltrated, harvested or evapotranspired (PDEP 2006; MDEQ 2010), others simply specify that this volume should be "managed" or "treated" on-site (AMEC and CWP, 2001; MPCA, 2005). Without volume reduction requirements, the water quality volume approach implicitly suggests that treatment of captured runoff will necessarily result in an "acceptable" pollutant load reduction, regardless of BMP type and pollutant wash-off dynamics. Indeed, in Minnesota or Michigan an 80 to 90% load reduction of total suspended solids (TSS) is expected when meeting this volume criterion (MDEQ 1999; MPCA 2005), as long as design requirements are respected. BMPs treatment performance has however been shown to vary significantly from a facility to another (CWP 2007) and the efficiency of treatment processes (such as settling, adsorption or filtration) in fact depend on pollutant and runoff characteristics. Particle size distribution can for instance noticeably affect the pollutant removal performance of detention ponds (Weiss et al. 2013). Expecting a level of performance from a BMP regardless of its design and site characteristics is thus probably inappropriate. Moreover, water quality volume criteria are often completed by drawdown requirements to provide (1) sufficient residence time for sediment to settle out and (2) sufficient capacity for the next event. As water residence times are generally expected not to exceed 24h to 72h hours, large outflow rates may be needed to empty stormwater facilities when high rainfall volumes are captured, which may impede their efficiency for smaller rain events.

Finally, while specific "de-pollution" processes (e.g. filtration, adsorption…) in BMPs can be significant for a highly polluted runoff, stormwater, treatment may not always be relevant for on-site management on residential watersheds where concentrations in runoff often remain relatively moderate. Recent studies indicate that (1) the concentration decrease at the outlet of LID practices often depends on the concentration at the inlet (Barrett 2005; Larm and Hallberg 2008) and that load reduction does not always result from this concentration decrease (associated with treatment or "de-pollution" processes) but more systematically tallies with runoff volume reduction (Davis 2007; Hunt et al. 2008; Trowsdale and Simcock 2011; Bressy et al. 2014). One could therefore argue that a diffuse pollution mitigation criterion would probably better be expressed as runoff volume reduction targets rather than a "water quality volume" (to be treated).

Water quality volume requirements alone therefore do not necessarily guarantee a particular level of pollutant reduction, but they do provide at least some water quality benefits over requirements based solely on managing flow-rates. Such policies' outcome probably depends on the guidance given to developers for BMP selection and conception which may promote volume reduction over "treatment and release" strategies. Besides, it should be acknowledged that "treatment and release" presumably remain consistent for more contaminated areas.

3. 2.2. Volume reduction strategies

"Volume reduction" or "permanent interception" implies that volumes captured in a facility will not later be discharged to sewer networks or surface waters. Although volume reduction is often specified as the best approach for stormwater management, "volume reduction criteria" do not systematically aim at providing pollution control and often address other environmental issues. In France, infiltration or "zero discharge" (total infiltration) regulations adopted by some sewer networks operators are essentially intended to prevent floods and CSO (HBCA 2010; SyAGE 2013), although national and regional agencies' guidance documents indicate that infiltration should generally be preferred for on-site pollution control (CERTU 2011; DRIEE 2012). Likewise, some states in the US require a fraction of the water quality volume to be infiltrated to maintain pre-development groundwater recharge and to preserve water table elevation, but this strategy is not systematically associated with pollution control (VANR 2002; NJDEP 2009). Conversely, in Oregon, New-York State or British Columbia in Canada runoff volume reduction pertains to both stormwater quantity and quality management. Chilliwack policy and design criteria manual states that "reducing volume at the source – where the rain falls – is the key to protecting […] water quality" (CH2MILL 2002). Likewise, it can be found in Portland Stormwater Management Manual that "infiltrating stormwater on site […] is a multi-objective strategy that provides a number of benefits including […] pollution reduction […]" (PBES 2008).

"Volume reduction" strategies probably provide less variable pollution control and could presumably be preferred over treatment criteria (e.g. "water quality volume"), as pollutant loads corresponding to infiltrated or evaporated volumes are entirely mitigated while additional pollution control may be obtained from treatment processes like filtration, adsorption or sedimentation. As for water quality volume criteria, the amount of water to be captured nevertheless significantly differs from a community to another (cf. table 2), and definition of performance targets, when justified, only relies on simple statistical rainfall analysis, similar to that described in 3.2.1 (BC-MWLAP 2002) or estimation of predevelopment infiltration volumes. Indeed, although British-Columbia guidelines indicate that such analysis is sufficient for setting performance targets (and continuous modeling is thus not always needed) (BC-MWLAP 2002), definition of an optimal "volume reduction" criterion for pollution control is arguably complex, as pollutant loads and runoff volume abatements may not be equal (because of temporal variability of concentrations in runoff). Furthermore, volume reduction criteria are either accepted as daily performance targets or management objectives for a design storm (cf. table 2); determination of corresponding storage volume is hence not straightforward and proper BMP design presumably requires providing sufficient guidance to practitioners to ensure that volume reduction objectives are met.

Country/Community	Volume targets	Details
US		
Iowa (IDNR 2003) (non-regulatory)	2 to 25 mm	Depending on soil characteristics
Vermont (VANR 2002) (regulatory)	0 to 10 mm	Depending on soil characteristics
Montana (MDEQ 2010) (regulatory)	12.5 mm	Design storm approach
New York (NYDEC 2015) (regulatory)	20 to 31 mm	90th percentile storm
Portland (PBES 2008) (regulatory)	Up to 86 mm	Design storm approach
Canada		
British-Columbia (BC-MWLAP 2002) (non-regulatory)	Up to 30 mm	Daily volume reduction capacity
France		
Paris (Nezeys 2013) (regulatory)	4 to 16 mm	Daily volume reduction capacity
Yerre Catchment (SyAGE 2013) (regulatory)	“Zero discharge”	Daily volume reduction capacity

Table 2 Illustration of “volume reduction” criteria for various communities - Volume targets are expressed as rainfall depth unless specified

Eventually, special attention should presumably be paid to the terms used for the definition of such management criteria. “Infiltration” may indeed either refer to temporary storage in upper soil layers prior to evapotranspiration or to water percolation down to aquifers. “Volume reduction” or “permanent interception” should therefore probably be preferred over “infiltration” since massive infiltration may not always be desired in highly pervious soils (which are more vulnerable to groundwater contamination), neither possible for low permeability substrates (which may however store non-negligible amounts of water and result in runoff volume reduction through evapotranspiration).

3. 3. Non-hydrologic criteria

3. 3.1. Concentration thresholds

Concentration thresholds in runoff or surface waters may sometimes be given for specific purposes, like direct discharge to surface waters regulation, In Europe, Environmental Quality Standards (immission standards) have been adopted under the Water Framework Directive 2000/60/EC for various contaminants. Nonetheless, assessing the impact of a stormwater management option on receiving water is generally complex and uncertain. As a consequence, regulations are often based on “emission criteria” which are much easier to handle, and may be adapted to the ecological status of receiving waters (Engelhard and Rauch 2008).

Maximum effluent concentrations are typically emission control criteria. However, like environmental quality standards, they usually remain mostly informative as no simple methodology can presently guarantee that a BMP will produce the expected concentrations for a given contaminant. As stated in a 2006 report to the California

State Water Resources Control Board (Currier et al. 2006), while the choice of BMP could be based on effluent concentrations or pollutant removal efficiencies from the literature, such approach may not be completely satisfactory as effluent concentrations and pollutant removal efficiencies usually depend on influent concentrations (Barrett 2005; Larm and Hallberg 2008) and are more generally highly variable (Park et al. 2010). Moreover, selection of stormwater management strategies in accordance with expected effluent concentrations pushes BMP design into the background as it implicitly assumes that for a given type of BMP design is unlikely to affect their performance. In the US, compliance with water quality standards is thus simply assumed to be met through the implementation of properly designed best management practices (US-EPA 2014). Similarly, “Design effluent objectives” for copper and zinc delivered in Auckland regional council’s unitary plan are supposed to be achievable with most BMP as long as design standards are respected (ARC 2013).

	Halifax (CA[1]) (HRM 2003)	London (CA[1]) (LCC 2001)	Auckland (NZ[1]) (ARC 2013)	Yonne (FR[1]) (MISEN-89 2010)
TSS	15 mg/l	15 mg/l	25 mg/l	50 mg/l
COD	-		-	50 mg/l
P	0.5 mg/l	0.4 mg/l	0.2 mg/l	-
Oil, grease	15 mg/l	15 mg/l	10 mg/l	5 mg/l
Cd	15 µg/l	8 µg/l	-	10 µg/l
Cu	30 µg/l	40 µg/l	12 µg/l	4 µg/l
Pb	50 µg/l	120 µg/l	-	500 µg/l
Zn	300 µg/l	50 µg/l	40 µg/l	2000 µg/l

Table 3 Comparison of maximum effluent concentrations for various contaminant ([1]CA=Canada, FR=France, NZ=New Zealand) (regulatory water quality standards)

Both effluent and surface water concentration targets therefore remain uncommon as design criteria (or only apply to large development rather than on-site stormwater control), as a concentration can hardly be directly related to best management practices design. Furthermore, verification and enforcement of such limitations would believably be difficult provided the variability of concentrations at the outlet of a BMP (Currier et al. 2006). Besides, definition of admissible effluent concentrations may be somewhat subjective and thresholds can noticeably differ from a community to another (see table 3), which indicates the lack of common agreement on what a “clean discharge” should be. It should additionally be outlined that concentration based criteria do not necessarily guarantee improvement of surface water quality. In the case of residential or relatively uncontaminated catchment, pollutant concentrations may remain low whereas runoff volumes are typically likely to increase as well as pollutant loads (MBWCP 2006).

In the context of on-site stormwater management, the definition of concentration thresholds for effluent or receiving water cannot totally be discarded, but these should probably remain informative and support the adoption of certain BMP solutions in the case of fairly contaminated urban runoff or sensitive receiving waters.

However, rather than assuming a given level of performance from a BMP, stormwater management facilities should be selected and designed in accordance with (1) water quality standards (themselves consistent with the ecological status of receiving waters) and (2) the pollutant removal processes that are likely to address these requirements (Clark and Pitt 2012).

3. 3.2. Load reduction approaches

In few cases, stormwater management guidelines may directly be based on numerical targets related to minimum pollutant loads reductions, instead of hydrologic criteria such as interception volumes or flow rate control. In Northern America or New Zealand such targets can generally be found as objectives rather than design criteria (e.g. treatment of “water quality volume” expected to provide an 80 to 90% TSS load removal) and is therefore not directly used for BMP design (IDNR 2003; MPCA 2005; ARC 2010b; MDDEP 2012).

In Australia, most authorities have on the contrary implemented annual load reduction objectives as a design criterion (MBWCP 2006; TCC 2011). Targeted contaminants are usually total suspended solids, nitrogen, phosphorous and gross pollutants (see table 4). Such an approach hence implicitly supposes that annual load reduction for these contaminants ensures removal of all other pollutants of concern. However, when considering highly contaminated urban surfaces, it is probably questionable whether loads associated with micro-pollutants will be “acceptable” (Strecker et al. 2004), especially if treatment only targets these four contaminants. Conversely, in the case of moderately contaminated areas, volume reduction is probably the only way to meet these load reduction objectives (as mentioned previously, BMPs are generally less likely to affect lower concentrations).

These annual performance targets might in fact simply originate from what is reasonably achievable with most conventional BMPs. In the US, the 80% TSS removal objective (supposed to be achievable when meeting volume based management criteria) specified in CZARA (Coastal Zone Act Reauthorization Amendment) guidance is “assumed to control heavy metals, phosphorous and other pollutants” and is adopted because “analysis has shown constructed wetlands, wet ponds and infiltration basins can remove 80% of TSS” (US-EPA 1993). Similarly, Australian TSS, TN or TP reduction targets are often similar to most BMP’s median efficiencies reported by Center for Watershed Protection (CWP 2007).

Authority	TSS	Phosphorous	Nitrogen	Gross pollutant
Parramatta Catchment (URSA 2003) (non-regulatory)	50 to 80%	45%	45%	70%
South East Queensland[1] (MBWCP 2006) (non-regulatory)	80%	60%	45%	90%
State of Victoria (VSC 2006) (regulatory)	80%	45%	45%	70%
City of Townsville (TCC 2011) (regulatory)	80%	60%	45%	90%

City of Logan (LCC 2013) (regulatory)	80%	55%	45%	90%
City of Melbourne (CM 2006) (regulatory)	80%	45%	45%	70%

Table 4 Annual pollutant loads reduction targets in Australia ([1]Capture and management of the first 10mm of runoff may alternatively be expected for site with less than 25% impervious area)

In Germany and Switzerland, while guidance documents are also based on a load reduction approach (DWA 2007; VSA 2008), an indicator system was adopted, accounting for both pollutant loads produced on urban surfaces and receiving waters' vulnerability to determine the level of treatment required. Although German standards were initially only addressing infiltration or direct discharge to the environment, they may be mentioned in local rules for treatment requirement before discharge to sewer networks (SW 2013). In DWA's guidelines (German association for water, wastewater and waste), dimensionless variables are introduced to quantify both air quality L (depending on traffic or land use) and surface contamination F (depending on cover type). A pollutant load indicator B (=L+F) or "emission value" can therefore be computed from catchment characteristics, and compared to an "admissible value" E depending on the sensitivity of receiving waters. A "reference value" D is eventually introduced so as to account for various BMP's efficiency for pollution control (no elements are however provided for the calculation of D values). If "emission value" is higher than "admissible value" (E<B), runoff treatment is required and 'emission value" may then be reduced to an admissible levels if BMP are implemented (E>B×D). This BMP selection procedure is summarized in figure2.

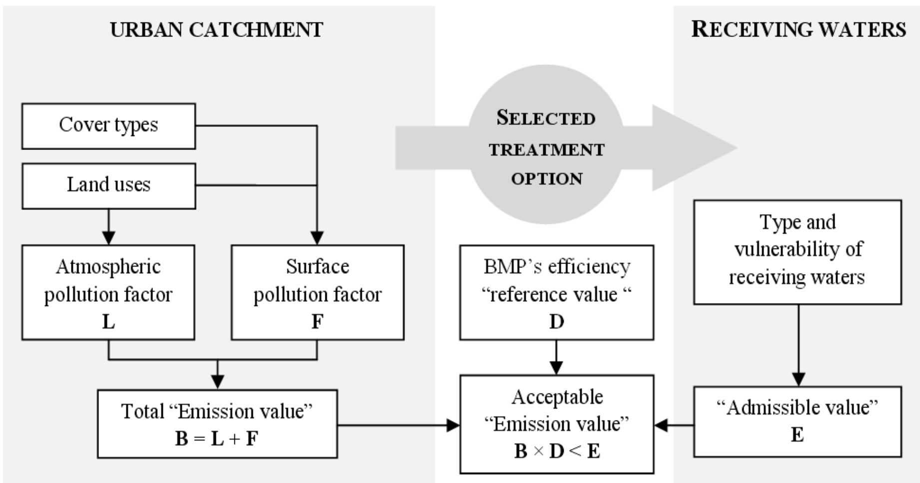

Figure 2 BMP selection process for pollution control according to German standards DWA-M-153 (DWA 2007)

While, somewhat equivalent to a load reduction approach, these metrics-based methods remain fundamentally different from Australian guidelines and can hardly be considered as "criterion-based". Indeed, whereas difficulties would have arisen from the use of mass unit pollution control targets (cf. 4.2.); loads calculation is here simplified and directly integrated to BMP design and selection tools. This example once more illustrates that, for a given management criterion, guidance documents given to developers might be a decisive factor in stormwater facilities design and LID implementation. Interestingly, DWA's standardized approach furthermore allows for both emission and immission control as BMP selection is based on both the vulnerability of receiving waters and catchment characteristics, which is relatively uncommon in stormwater regulations. Nonetheless, such a method may be regarded as a "black-box" since it does not provide any scientific rationale for the determination of emission or BMP efficiency values.

4. FROM MANAGEMENT CRITERIA TO LID IMPLEMENTATION

Several stormwater management criteria have been identified. While their relevance for pollution control has been discussed from a relatively theoretical standpoint, their relationship to low impact development implementation (through BMP selection and design) has to be investigated

4. 1. Preferring permanent interception over capture and release

Flow-rate criteria and their relevance for on-site management strategies have been investigated by Petrucci (2012) who found that sizing methods often "do not guarantee […] systematic implementation of LID solutions". Indeed, flow-rate control necessarily requires temporary storage of runoff volumes; detention facilities are therefore the easiest way to comply with these criteria. In Hauts-de-Seine county (France), where stormwater management rules consist in 2 to 5 l/s/ha flow-rate limitation and sizing approach is mainly based on a storage volume calculation (CG92 2010), underground or mineral detention facilities remain very widespread (Lehoucq et al. 2013), although probably not suitable for volume and pollutant loads reduction.

Unlike flow-rate limitation, "water quality volume" definition implies that captured volume should not only be detained but also treated, and should therefore probably promote practices that are more suitable for pollution control. These criteria are however often completed with time-to-drain requirements. Expecting a 25mm runoff volume to drain within 24 hours would for instance be similar to a 3 l/s/ha outflow rate limitation (assuming constant outflow rate). While permanent interception would generally require large seepage surfaces to promote infiltration and evapotranspiration (so as to comply with volume drawdown requirements), developers may hence be more likely to adopt the most compact stormwater practices, based on treatment rather than infiltration.

Inversely, if volume reduction policies were adopted, runoff management in small and decentralized LID practices could presumably become a relevant and cost effective solution for both runoff and pollutant control. Indeed, green roof implementation, which is a typically distributed runoff reduction method, could probably be preferred to underground detention facilities, and become like in Philadelphia a "tool of choice" for space constrained developments (Horwitz-Bennett 2013). However, demonstrating compliance with “volume reduction” criteria may remain difficult for practitioners and development of easy-to-use methods may be needed to guarantee optimal BMP design (PBES 2008).

4. 2. Uncertainties associated with BMP design from non-hydrologic criteria

Assessing pollutant removal efficiency of LID practices is generally difficult and simplified methods are hence often given to developers for BMP design so as to demonstrate compliance with loads reduction criteria. While such approaches do not require extensive knowledge about processes associated with pollutant removal, these may however be questionable.

New Jersey guidelines assume that TSS removal rates can be calculated from median efficiencies given for various BMPs (Balascio and Lucas 2009). Corresponding pollutant removal rates are hence supposed to be achieved as long as these practices are sized for “water quality volume” treatment (NJDEP 2009). While such an approach recognizes that treatment of a given volume may not result in same TSS load reduction in every BMP, calculated rates remain approximate and arbitrary (Balascio and Lucas 2009) (as they do not consider sediment characteristics or BMP design). Similarly, in Australia and Germany, average pollutant removal efficiencies associated with LID solutions are expected under specific design conditions. In Greater Brisbane, 1.5% of drainage area for bio-filtration filter media area is for example “deemed to comply” with water quality objectives for smallest developments (SEQ-HWP 2010). In other regions, stormwater management manuals integrate “performance curves”, linking BMP’s size parameters (e.g. length or area) to annual TSS or nutrient removal rates (NTDPI 2009; TCC 2011). In Germany, although an indicator-based system is used, design approach remains very similar to Australian “deemed to comply” solutions, with treatment values given for various practices and design options (DWA 2007). As mentioned previously, many elements in treatment BMP design, like filter media composition in bio-retention systems, or vegetation in sedimentation devices, may influence their pollutant removal efficiency (Scholes et al. 2008; Davis et al. 2009). Direct relationship between pollutant removal and BMP’s size assumption may therefore only be relevant under strict design conditions.

Alternative design approaches in Australia include use of modeling software MUSIC, for larger developments (SEQ-HWP, 2010). Nevertheless, although presumably more satisfactory, modeling may not systematically be used by practitioners and believably requires sufficient knowledge from users, as processes associated with runoff pollution remain poorly understood (Gromaire et al. 2007).

4. 3. A need for better guidance to promote LID practices

The example of non-hydrologic criteria indicates that the existence of simplified methods is generally a fundamental prerequisite for successful stormwater practices implementation. More generally, lack of sufficient guidelines to determine if LID practices are consistent with existing rules and standards may therefore be a significant impediment to their implementation (Roy et al. 2008).

Precise flow-rate limitations may for example be somewhat rigid, as discharge rate is in any case expected not to exceed a given value. While green roofs have been demonstrated to provide flow-rate attenuation (Carter and Rasmussen 2006; Stovin et al. 2012) they are for example not very likely to comply with such rules (unless they are equipped with flow-regulators) since their effect on peak flow rate remains variable from a rain event to another. Inversely, storage facilities equipped with flow-limiting devices would probably be preferred by practitioners, as flow regulator installation is the simplest way to ensure respect of design criterion. Similarly, although most conventional stormwater facilities can easily be sized from volume based criteria, it may remain difficult to account for volume reduction in non-infiltration BMP or non-structural practices. Indeed, while facilities such as bioretention basins equipped with drains or impervious liners can nevertheless provide significant runoff volume abatement through evapotranspiration from soil surface layers (Hatt et al. 2009; Daly et al. 2012) and may be relevant for volume control under restrictive soils condition, their hydrologic functioning is not yet fully predictable.

In the US, several local authorities have therefore adopted or developed innovative methods so as to promote and account for the effect of sustainable on-site and non structural stormwater management practices (MDE 2010; Battiata et al. 2010; PWD 2011; Gallo et al. 2012). In Philadelphia, roofs effective imperviousness, used for runoff volume computation, may indeed be reduced when disconnected (PWD 2011). In Seattle, where both flow rate and volume control are required, a simplified "Pre-sized approach" based on a crediting system, representing the degree to which selected "pre-sized" solutions comply with management requirements, has been adopted for small developments (CS-SPU 2009). An equivalent mitigated area can therefore be directly calculated for a various LID practices. Similarly, Pennsylvania, Georgia, Minnesota or Maryland guidelines allow for reduction of volume requirements if LID solutions are adopted (AMEC and CWP 2001; PDEP 2006; MDE 2010) (cf. table 5).

Authority	LID practice	Volume reduction approach
Pennsylvania (PDEP 2006)	"Minimizing soil compaction"	$\Delta V = A \times 6.4 / 1000$ *Where: ΔV = net volume reduction (m^3), A = Area of minimal soil compaction (m^2)*
Maryland (MDE 2009)	"Grass swales""	$P_E = 254 \times SA / DA$ *Where: P_E = equivalent rainfall volume managed in the*

Georgia (AMEC and CWP 2001)	“Rooftop disconnection”	*swale (mm), A = drainage area, SA = swale surface area* $\Delta V = 30.5 \times C \times (A\text{-}DIA)$ *Where: ΔV = net volume reduction (m^3), C = runoff coefficient, A = site area (m^2), DIA = disconnected impervious area(m^2)*

Table 5 Illustration of volume reduction approaches for various LID practices

While such crediting systems will obviously facilitate and promote LID implementation, they often rely on several simplifying hypotheses regarding BMP efficiency for runoff and pollution control (Battiata et al. 2010). Definition of management criteria and guidance, balancing scientific validity and ease of use, could therefore be a real challenge for regulators and environmental agencies.

5. CONCLUSION AND PERSPECTIVES

Four categories of criteria for on-site runoff pollution control, namely flow-rate limitations, “water quality volumes”, volume reduction and non-hydrologic targets have been identified and analyzed based on a review of management practices adopted in different countries. Regarding the relevance of these stormwater management criteria for on-site pollution control, this study suggests that:

- “Treatment and release” strategies may not be relevant for moderately contaminated runoff. As a consequence, volume reduction (through infiltration, evapotranspiration or re-use) should generally be (e.g. where feasible) the preferred approach for on-site pollution control.
- Determination of an “optimal” permanent interception volume remains an open question and further investigations are required to better understand the relation between targeted volume and long-term pollutant load removal and find out whether standardized sizing approaches based on a single criterion are relevant for on-site pollution control.
- While volume reduction can be expected to assure minimum pollution control, the benefits associated with pollutant removal processes should still be considered for increased BMP efficiency. A better understanding of these “de-pollution” processes is thus needed to correctly address requirements such as maximum effluent concentrations which may arise from environmental standards or to provide acceptable pollution control for more contaminated urban surfaces.
- Volume reduction is typically an emission control strategy which does not account for the vulnerability of receiving waters. While recommendation about volume reduction targets may be provided, it is

essential to acknowledge that design criteria should be adapted to site-specific requirements to meet environmental quality objectives.

Besides, Low Impact Development implementation and proper BMP design not solely depend on stormwater management criteria, but also on guidance documents provided to practitioners. The lack of technical expertise is indeed the major factor in the persistence of traditional management and design approaches at the local scale. Diffuse pollution control is a relatively recent stormwater management objective for local communities that have traditionally focused on flood or CSO control. Demonstrating that volume reduction is compatible with existing flow-rate based requirements and provide benefits for both peak-flow and pollutant control is thus crucial for a wide implementation of LID practices. Finally, suitable design methods should be believably developed so as to deal with site specific constraints and to overcome difficulties arising from demonstration of compliance with stormwater management requirements.

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